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title

RESEARCH AND DEVELOPMENT OF AN OPEN-CYCLE FUEL CELL SYSTEM

(NASA Contract No. NAS8-2696)

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Prepared for

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By

SPACE AND DEFENSE
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30 APRIL 1964 23p one

FOREWORD

This report was prepared by the Aerospace Power Systems Section, Research Division, Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin, under NASA Contract NAS8-2696. The work was administered under the direction of the Electrical Components and Power Supplies Section, Astrionics Division, NASA, Huntsville, Alabama. Mr. Richard Boehme is the technical supervisor for NASA.

This Seventh Quarterly Report covers the work completed from 1 January to 31 March 1964, and is submitted per the 1 January 1964 Contract Modification.

Management direction at Allis-Chalmers includes Mr. Will Mitchell, Jr., Director of Research; and Dr. Powell A. Joyner, Mr. D. T. Scag and Mr. W. W. Edens, Assistant Directors of Research. The project is supervised by John L. Platner, Manager and Paul D. Hess, Chief Engineer. The Project Leader is David P. Ghere.

The report was written by James Euclide, R. Opperthauser and B. R. Nichols.

ABSTRACT

Mathematical investigations of the Static Vapor Pressure Control System, which are being experimentally verified by gas chromatograph studies, are discussed.

A mockup of a gas cooled fuel cell system has been assembled. The results of initial tests are described.

Progress in design, fabrication and assembly of a 2000 watt experimental fuel cell system is reported.

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1.0 SUMMARY

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The Static Vapor Pressure Control Studies have proceeded to the point where experimental data from the gas chromatograph tests are being compared with computer solutions of the theoretical mathematical model. Agreement between experimental and theoretical data was good on initial tests.

A mockup of a gas cooled fuel cell system has been assembled and initial testing has started. The initial tests have confirmed the feasibility of the approach.

An amendment to the contract requires construction of a 2000 watt experimental fuel cell system instead of the 1500 watt unit previously specified. Fabrication of this unit is progressing well.

Author

2.0 INTRODUCTION

Under the contract modification which took place during the last quarter, a large portion of the work is to be directed towards fabrication of a 2000 watt experimental fuel cell system. A limited amount of more fundamental work is being conducted in conjunction with the assembly of the unit. This includes development and experimental verification of a mathematical model of the Static Vapor Pressure Control System.

3.0 STATIC VAPOR PRESSURE CONTROL STUDIES

In an operating fuel cell which uses the Static Moisture Removal technique, the reactant flow is "dead-ended" in the cell. Except for periodic purges to remove accumulated inert gases, there is no flow of reactants from the cell. As the reactants enter the cell and are distributed over the electrodes to the reaction sites, a small pressure gradient develops when the reactants are consumed.

A simplified mathematical model of the system was developed from an analytical study of the Static Moisture Removal mechanism. This model assumes that each segment of the electrode operates at a common current density, the cell temperature is uniform, and the flow rate of reactants is independent of the direction normal to the reactant flow. Variation of the total pressure within a cell is neglected.

Under the above conditions, the fuel cell may be represented as shown in Figure 1, where conditions are constant in the direction perpendicular to the paper and the dimension of the cell in that direction is unity. Two variations of reactant flow are possible:

(1) Parallel flow, where both hydrogen and oxygen enter at the same end of the cell,

(2) Counter flow, where hydrogen and oxygen enter at opposite ends of the cell.

For brevity, only the case of parallel flow will be discussed here. All that is involved in changing to counter flow is a change in the indexing of the variables.

The length of the cell may be divided into n equal elements; each element being numbered sequentially starting with one at the hydrogen inlet. Consider a general element, i, shown in Figure 1. A water balance on the hydrogen side of this element gives

(see next page for equation)

$$W_{ci} = \frac{D_M A}{n \delta w}(C_{Hi} - C) - \frac{R_H m_H I}{R \mathcal{F} n}\left[\left(\frac{P_{VHi-1}}{P - P_{VHi-1}}\right)(n - i + 1)\right.$$

$$\left. - \left(\frac{P_{VHi}}{P - P_{VHi}}\right)(n - i)\right] - \frac{R_H m_H I}{R \mathcal{F} n} \qquad (1)$$

$$+ \frac{D_H A_H n}{L R T}\left(P_{VHi+1} - P_{VHi-1}\right)$$

The first term on the right of Equation (1) represents the water transported through the water removal membrane. The second term is the net transport of water into the element with the flowing hydrogen stream. The third term is the amount of water generated in the element due to the consumption of reactants. The fourth term is the net transport of water into the element by diffusion of water vapor from adjacent elements through the hydrogen stream.

Solution for the actual electrolyte concentration in the cell begins by making an initial guess at the concentration on the hydrogen side. Since the specification of concentration at a given temperature uniquely determines the vapor pressure of the electrolyte, Equation (1) may be solved for W_{c_i}, $i = 1, 2, 3, \cdots m$. Then the distribution of electrolyte concentration on the oxygen side may be calculated from

$$C_{oi} = C_{Hi} + \frac{\delta n}{D A}\left(W_{ci} - \frac{R_H m_H I}{R \mathcal{F} n}\right) \qquad (2)$$

A water balance on the oxygen side gives

$$W'_{c_i} = \frac{R_o m_o I}{R \mathcal{F} n} \left[\left(\frac{P_{VO_{i-1}}}{P - P_{VO_{i-1}}} \right) (n - i + 1) - \left(\frac{P_{VO_i}}{P - P_{VO_i}} \right) (n - i) \right] \quad (3)$$

$$- \frac{D_o A_o n}{R L T} \left(P_{VO_{i+1}} - P_{VO_{i-1}} \right)$$

Initially, W_{c_i} and W'_{c_i} will differ by an amount which will depend on the accuracy of the initial guess of electrolyte concentration. The assumed concentration distribution can be made more nearly equal to the actual concentration distribution by solving for vapor pressure (and hence electrolyte concentration) in the equation

$$\frac{D M A}{n \sigma w} (C_{H_i} - C) - \frac{R_H m_H I}{R \mathcal{F} n} \left[\left(\frac{P_{VH_{i-1}}}{P - P_{VH_{i-1}}} \right) (n - i + 1) - \left(\frac{P_{VH_i}}{P - P_{VH_i}} \right) (n - i) \right] \quad (4)$$

$$- \frac{R_H m_H I}{R \mathcal{F} n} + \frac{D_H A_H n}{L T R} \left(P_{VH_{i+1}} - P_{VH_{i-1}} \right) =$$

$$(1 - \psi) w_{c_i} + \psi w'_{c_i}$$

where ψ is a number between 0 and 1. If $\psi = 1/2$, the right-hand side of Equation (4) is the arithmetic average of W_{c_i} and W'_{c_i}.

The values obtained from Equation (4) can be used to calculate improved values for the concentrations on the oxygen side, and so the iteration will proceed until

$$\left| W_{c_i} - W'_{c_i} \right| \leq \epsilon \qquad i = 1, 2, 3, \cdots n$$

where ϵ is the desired accuracy.

This problem has been programmed for the IBM 704 Computer and solutions to several representative problems have been obtained. Some of the physical constants involved in the equations are not accurately known. These are: The diffusion coefficient, D; the effective thicknesses for diffusion in the liquid state, σ and σ_w; and the effective area for diffusion through the water removal membrane, μ A. Various values of these constants have been used in obtaining solutions and the resulting electrolyte concentration distributions have been compared with experimental results obtained from gas chromatograph measurements. Good agreement between experimental data and calculated results has been obtained.

NOMENCLATURE

A	active cell area (cm^2)
A_H	cross section of hydrogen flow channel (cm^2)
A_O	cross section of oxygen flow channel (cm^2)
C	water concentration in electrolyte in water removal cavity (gm of water/cc of electrolyte)
C_H	water concentration in electrolyte on hydrogen side of cell (gm of water/cc of electrolyte)
C_O	water concentration in electrolyte on oxygen side of cell (gm of water/cc of electrolyte)
D	diffusion coefficient of water in the electrolyte solution as held in the asbestos matrix (cm^2/sec)
D_H	diffusion coefficient of water in hydrogen at cell temperature and pressure (cm^2/sec)
D_O	diffusion coefficient of water in oxygen at cell temperature and pressure (cm^2/sec)
$\mathcal{F}$	Faraday constant (96,000 coulombs/chemical equivalent)
I	cell current (amp)
L	dimension of cell in direction of reactant flow (cm)
m_H	chemical equivalent weight of hydrogen (gm)
m_O	chemical equivalent weight of oxygen (gm)
P	total pressure in cell ($dynes/cm^2$)
P_{VH}	vapor pressure on hydrogen side of cell ($dynes/cm^2$)
P_{VO}	vapor pressure on oxygen side of cell ($dynes/cm^2$)

R	gas constant for water vapor (erg/gm °K)
R_H	gas constant for hydrogen (erg/gm °K)
R_O	gas constant for oxygen (erg/gm °K)
T	absolute temperature of cell (°K)
W_c	net exchange of water between the hydrogen and oxygen streams, as calculated from a water balance on the hydrogen side (gm/sec)
W'_c	net exchange of water between the hydrogen and oxygen streams, as calculated from a water balance on the oxygen side (gm/sec)
δ	distance between the electrolyte interfaces on the hydrogen and oxygen electrodes (cm)
δ_ω	distance between surface of water removal membrane and interface of electrolyte in the membrane support plaque (cm)
ϵ	allowable error for convergence in the iterative solution (gm/sec)
μ	ratio of effective area for diffusion through the water removal membrane to the cell active area (unitless)
α	acceleration factor for use in the iteration procedure (unitless)

4.0 THERMAL MOCKUP

The thermal mockup of a gas cooled fuel cell system discussed in the Sixth Quarterly Report has been assembled and initial tests have been completed. More extensive design evaluation testing is presently being conducted. The initial tests established the feasibility of the approach. Figure 7 from the Sixth Quarterly Report is repeated as Figure 2 for reference during the following discussion.

4.1 Preliminary Component Tests

Prior to assembling the mockup, several preliminary tests were conducted on the coolant circulating fans. The fans selected were "off-the-shelf" items driven by 400 cycle, 115 volt motors at a rated speed of 22,000 rpm.

Several tests were conducted to check the performance of the coolant circulating fans. These tests were conducted with air, helium and hydrogen. The results are compared to the manufacturer's curve on Figure 3. The results, providing a reference for future tests, indicated that the performance was similar to, but slightly greater than the manufacturer's prediction. Power input was slightly lower than expected, as shown in the lower pair of curves.

A short initial test was run with the canister evacuated to 10 microns to determine the friction losses of the motor and fan. These indicated that each fan-motor combination had a loss of about 42 watts with no circulation of gas. Figure 4 shows the actual power required to circulate hydrogen and helium at the conditions indicated on the curve. This power includes the loss from the fan efficiency, but not the motor efficiency. Based on these figures, the motor efficiency is about 30%. A special design for this application could be made with a considerably higher efficiency. However, the power required to circulate the gas would remain essentially the same depending only on the fan efficiency.

Incorporated into the mockup was a compact heat exchanger. This prototype heat exchanger was designed for the 2000 watt experimental fuel cell system. The heat exchanger can be seen in Figure 5, which is a photo of the thermal mockup with the canister and fans removed.

The canister was fabricated from 0.040" magnesium with 0.5" magnesium flanges and end plates. The canister was proof tested to 7 atmospheres and then maintained at 4.4 atmospheres of hydrogen for over 100 hours at 90° C. Pressure drop was less than the instrumentation sensitivity or less than 0.2%.

4.2 Initial System Tests

After the preliminary component tests, the fans were installed in the thermal mockup, the canister was installed and insulated, and testing commenced. A short initial run was conducted with air at the same density as hydrogen at 2.4 atmospheres and 80° C in order to check out the system. Initial tests are being conducted with helium at 2.4 atmospheres. The capacity of the cooling system was deliberately oversized during design so that helium could be used for the initial testing. After alterations and improvements to the system have been made, final testing will be conducted using hydrogen as a coolant.

The tests conducted to date have provided valuable information in several areas. It has been definitely verified that the system is capable of removing at least 1600 watts of heat. This is approximately the amount of waste heat produced by a 2200 watt fuel cell module. In some areas, the difference between the design temperature and the actual temperature was greater than desired. In all cases, this could be attributed to uneven coolant flow distribution. Changes in baffling and ducting are being made to provide:

(1) A more even proportional flow in both directions along the fins,

(2) A more even distribution from top to bottom of the module.

In addition to the thermal mockup tests, a simplified mockup was made to check some of the ideas proposed for the cooling system for the 2000 watt experimental model. This mockup was used to check the effect on flow distribution and pressure drops of some proposed changes in the cooling system. Among the changes checked were a different duct design and flow path, an alternate heat exchanger which would be positioned in the duct, different fin thickness and spacing, and a different model fan. About one-half of the total pressure drop was found to be along the fins of the fuel cell module. The tests were run with air at atmospheric pressure.

5.0 EXPERIMENTAL FUEL CELL SYSTEM

The contract has been amended to construct a 2000 watt experimental fuel cell system, instead of the 1500 watt system formerly specified. The design of the fuel cell module has been verified by preliminary testing with two and four-cell modules. Fabrication of many of the components for the module has been completed with the balance to be finished during the coming quarter. The fuel cell module will consist of 35 units electrically connected in series. Each unit will be made up of two cells electrically connected in parallel.

The fuel cell module will be cooled by a gas cooling system similar to that discussed in the section on the thermal mockup. Although the fuel cell system is being designed to permit additional flight type hardware for other subsystems to be easily incorporated, initial tests will be conducted primarily with the fuel cell module and cooling system. The majority of instrumentation and controls (such as reactant pressure controls) will be supplied by laboratory components during the first phase. Design of the cooling system is progressing well. Fabrication of components for the cooling system will commence as soon as fabrication of the module components is completed.

Experimental models of two types of vapor pressure control components have been tested. The first type was a mechanical relief valve which was fully adjustable over the range from 0.1 to 1.0 atmospheres. This valve controlled the pressure within $\pm$ 1 mm Hg during initial tests. Further tests on an operating fuel cell proved that it could control the cavity pressure adequately and verified the feasibility of the mechanical relief valve principle for this application.

As a second approach, an electronic controller has been developed and tested. This controller utilizes a signal from the pressure transducer monitoring the cavity pressure, to operate a solenoid valve which opens to vacuum. Tests on operating cells proved the method to be feasible.

6.0 FUTURE WORK

During the next quarter the following work is planned:

(1) Continue Static Vapor Pressure Control Studies

(2) Complete testing of Thermal Mockup

(3) Assemble Experimental Fuel Cell System.

SIMPLIFIED REPRESENTATION OF A CELL OPERATING WITH STATIC MOISTURE REMOVAL

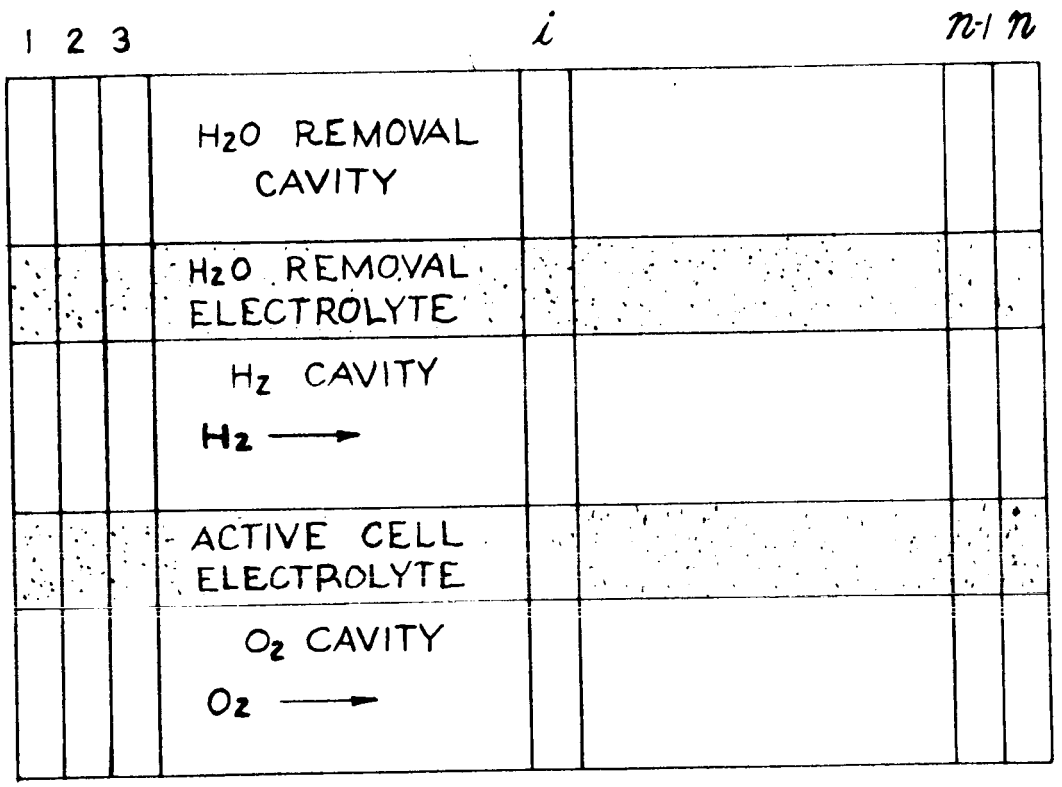

FIGURE 1

THERMAL MOCK-UP OF FUEL CELL SYSTEM WITH GAS COOLANT

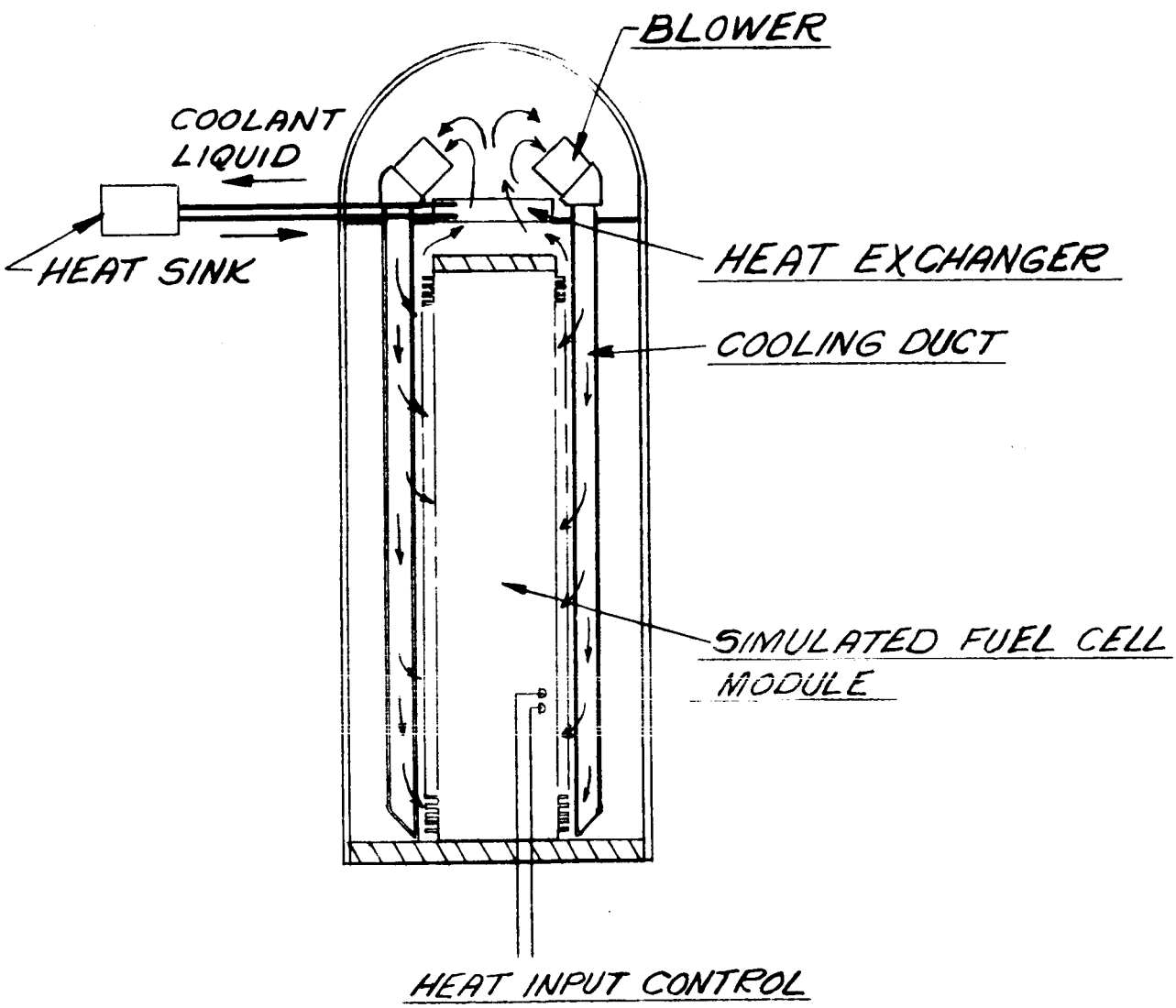

FIGURE 2

PERFORMANCE CHARACTERISTICS

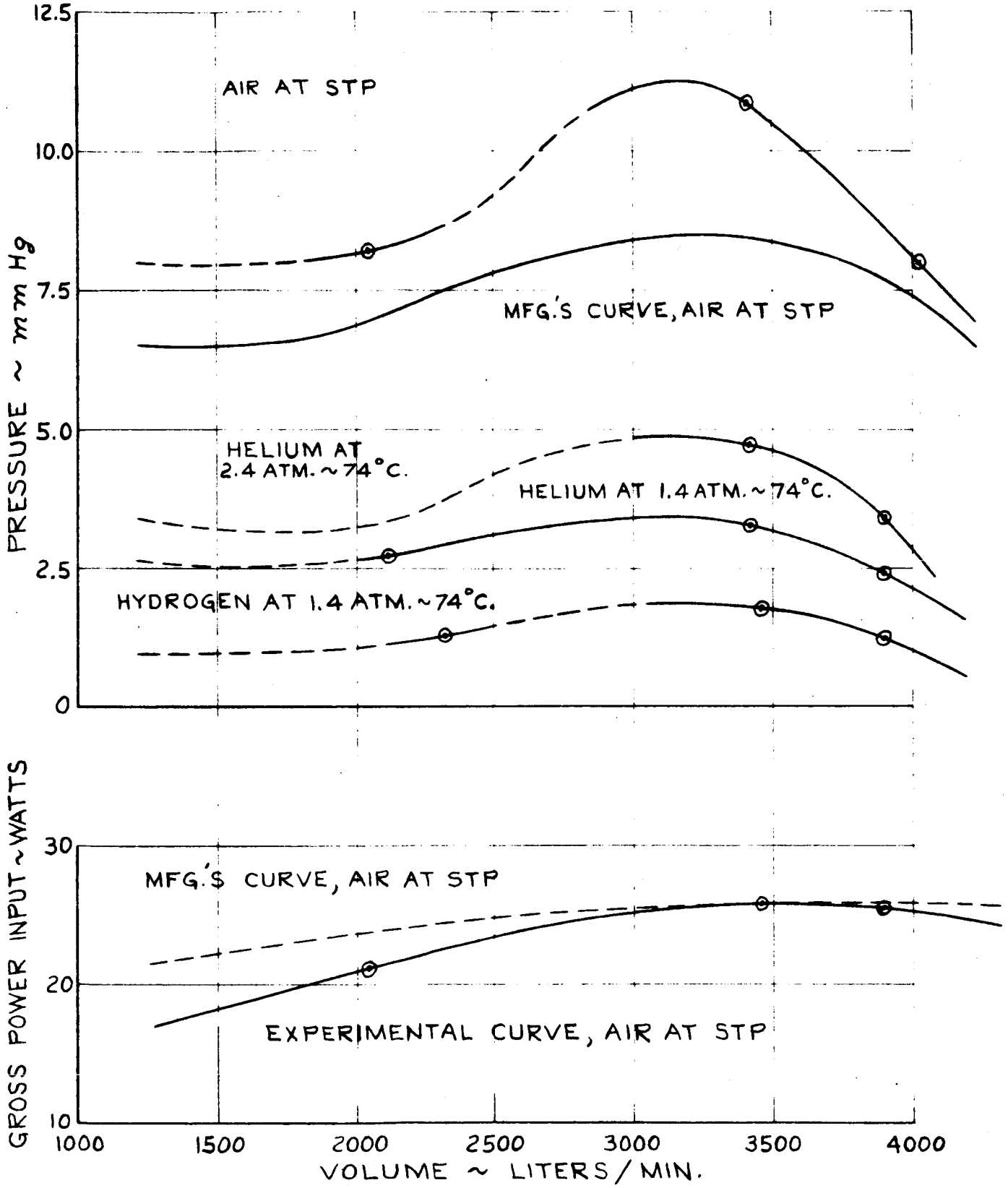

FIGURE - 3

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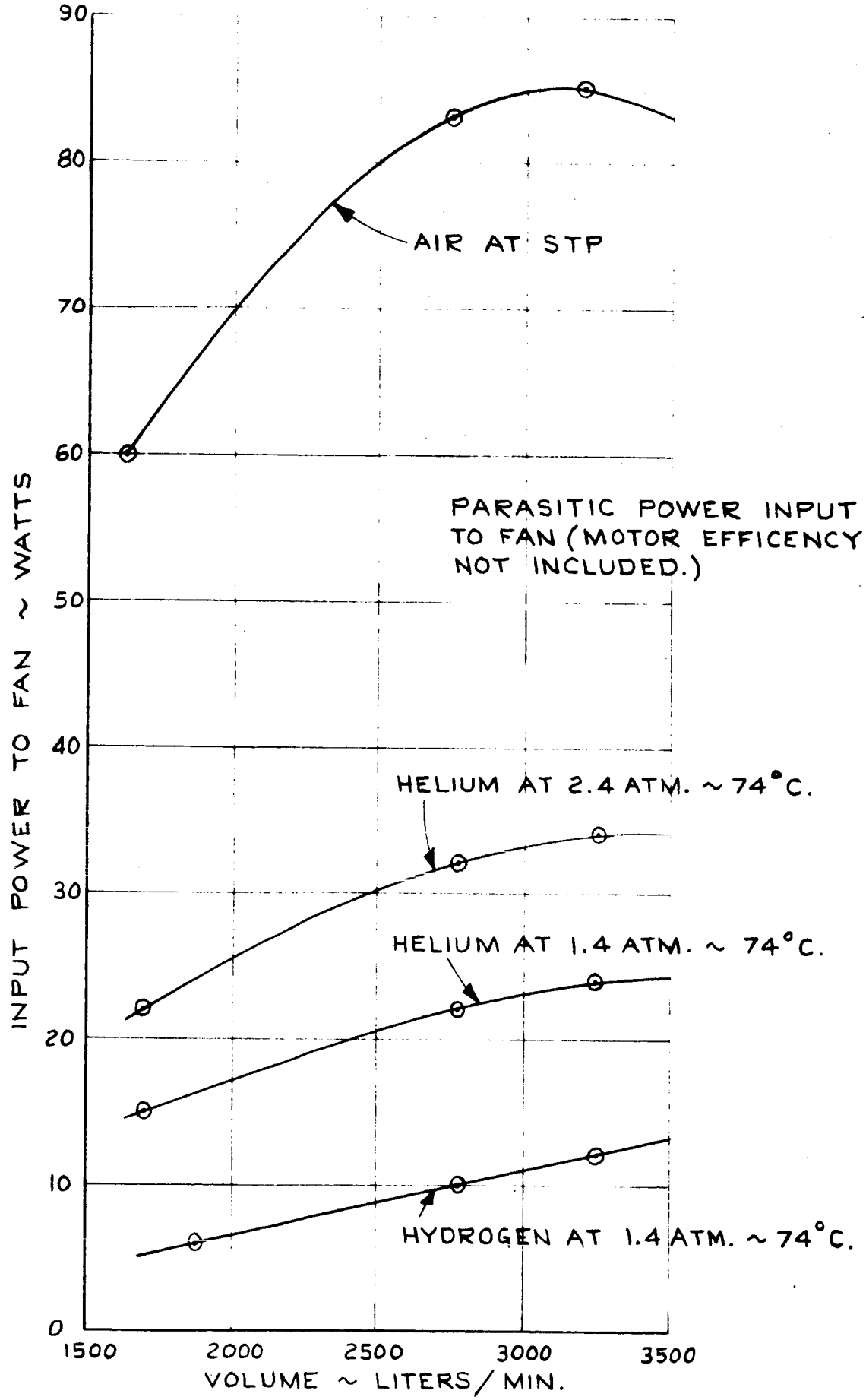

FIGURE - 4

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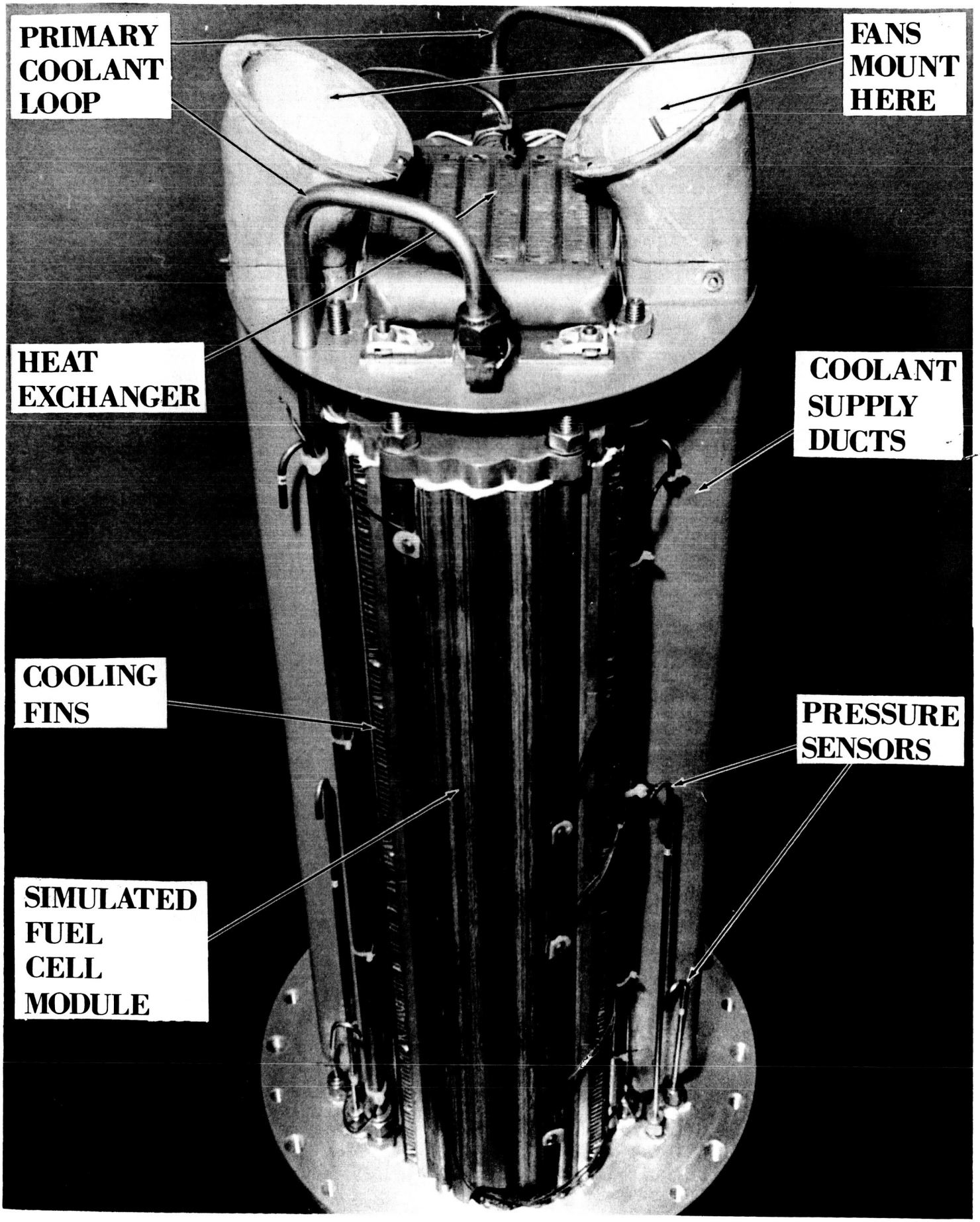

THERMAL MOCKUP

FIGURE 5